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3D Printers for Food Printing – Advantages and Drawbacks of Market Ready Technical Solutions

Drukarki 3D do druku żywności – zalety i wady rynkowych rozwiązań technicznych

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Abstract: The article takes a closer look at the basics of food 3D printing techniques in order to point out the real problems of this technology, especially through the perspective of the latest technical solutions (3D printers) available on the market in 2022. Food 3D printing technique is attracting the interest both in research and on the market. In the case of food, the most common technique used is paste extrusion, in which the material is placed in a syringe-shaped container and extruded while the print head moves and puts on the layers one by one, reproducing the final shape. Although research has been done on other additive processes, such as binder jetting and selective laser sintering using powdered food products, it is still debatable whether these processes are feasible for food printing.

Keywords: additive printing, 3D printing, food, extrusion, 3D food printer.

Streszczenie: Artykuł przybliża podstawy techniki druku 3D w przypadku żywności, aby wskazać realne problemy tej technologii, zwłaszcza z perspektywy najnowszych rozwiązań technicznych (drukarek 3D) dostępnych na rynku w 2022 roku. Technika druku 3D żywności budzi coraz większe zainteresowanie zarówno w badaniach naukowych, jak i na rynku. W przypadku żywności najczęściej stosowaną techniką jest ekstruzja pasty – materiał umieszczany jest w pojemniku w kształcie strzykawki i ekstrudowany, podczas gdy głowica drukująca porusza się i nakłada warstwy jedna po drugiej, odtwarzając ostateczny kształt. Chociaż przeprowadzono badania nad innymi procesami addytywnymi, takimi jak strumieniowanie spoiwa i selektywne spiekanie laserowe z wykorzystaniem sproszkowanych produktów spożywczych, nadal jest dyskusyjne, czy procesy te są wykonalne w przypadku drukowania żywności.

Słowa kluczowe: druk addytywny, druk 3D, żywność, ekstruzja, drukarka 3D żywności.

1. Introduction

3D printing is an additive multilayer printing, which allows the production of three-dimensional objects based on a three-dimensional digital design. 3D food printing technology was first developed as a result of research conducted at Cornell University, USA, and the printer model developed there – Fab@Home Model 1 and 2 was used to print paste-like food materials by extrusion (Periard, Schaal, Schaal, Malone, and Lipson, 2007).

3D printing presupposes and enables a new way of creating food products, especially those that cannot be easily produced by conventional methods due to complex geometry and interior structures. At the same time, the small-scale manufacturing of products by 3D printing enables the simplification of the supply chain through flexible, on-demand local food production (Jayaprakash et al., 2020); expansion of the range of ingredients used in food production (e.g. use of food waste/by-stream); providing food companies with new opportunities to interact with their consumer (Blurhapsody, 2022) and finally, enabling personalised nutrition (Liu and Zhang, 2019) and consumer empowerment (Caulier, Doets, and Noort, 2020).

By building on existing 3D printing techniques that are already exploited in industry, efforts were made to develop various 3D printing technologies useful in food printing, including extrusion-based printing, binder jetting, inkjet printing and selective laser sintering. Given the complex composition of food, the fact that it includes ingredients that can be considered the building structure of the product such as starch, protein and fibre, and those that act as plasticisers (fat, water and soluble sugars), the simple translation of printing techniques has proven to be extremely difficult.

2. Methods of 3D printing suitable for food products manufacturing

Among existing technologies, extrusion-based food printing was found to be the easiest to technically resolve due to its simplicity (Sun, Zhou, Yan, Huang, and Lin, 2018) and the fact that extrusion processes for multi-component pastes are well-known and widely used in conventional food processes. Currently, extrusion 3D printing has been used for, among others. protein gel (Liu, Bhandari, Prakash, Mantihal, and Zhang, 2019; Liu and Zhang, 2019), surimi (Gudjonsdottir, Napitupulu, and Petty Kristinsson, 2019), vegetable paste (Zhu, Stieger, van der Goot, and Schutyser, 2019), dough (Pulatsu, Su, Lin, and Lin, 2020), and chocolate (Hao, Li, Gong, and Xiong, 2019).

During extrusion 3D printing, semi-solid food material in a syringe is extruded from a nozzle onto a platform and deposited layer by layer, forming a 3D structure according to a digital design. The extrusion operation itself can be assisted by air pressure or mechanical force in a pneumatic, piston or screw system (Sun et al., 2018). Stamping requires materials to be characterised by the properties of pseudoplastic liquids, exhibiting shear thinning behaviour. At the same time, these materials must be characterised by rapid structural recovery after deposition to form a self-supporting structure. From a materials science point of view, food is a complex multi-polymer system with varying characteristics, the proper selection of which makes it possible to produce a material capable of being pressed at ambient temperature (e.g. printing dough or vegetable puree).

3D printing techniques based on the formation of a three-dimensional structure as a result of the binding or sintering of powders make it possible to solve some of the problems of additive extrusion printing, such as the production of complex, porous spatial shapes. In particular, selective laser sintering (SLS) is a 3D printing technique that allows product shape design and local control of mechanical properties. Unsintered powder provides the necessary support in 3D shapes that contain voids and overhangs, for which in extrusion printing it is necessary to print additional support structures. This advantage makes the SLS technique more suitable for processing complex macroscopic products. On a smaller length scale, SLS allows for greater spatial resolution, resulting in greater flexibility for the local adjustment of mechanical properties (Jonkers, van Dommelen, and Geers, 2022).

2.1. Extrusion

In the technique using paste extrusion, three mechanisms have been developed for extruding mass from a syringe, i.e. piston-driven, pneumatic or screw-driven (Schwab et al., 2020), with the piston-driven mechanism being the most commonly used for food materials. In this solution, a stepper motor is programmed to generate a linear motion of the piston to push the food material out of the nozzle. The extrusion rate parameter (i.e. the volumetric flow rate of the material) can be controlled by adjusting the speed of the motor, which simultaneously must be synchronised with the speed of the head movement to achieve the desired material layer formation (Sun et al., 2018).

In a pneumatically driven system, air pressure generated by a pump pushes the food material out of the syringe mouth, and the extrusion rate can be controlled by adjusting the air pressure. This system is more suitable for printing paste or gel food materials with relatively low viscosity due to the limited ability to apply force via pressure, and is often used in bioprinting applications for printing hydrogels.

In a screw system, a motor drives the movement of a screw that continuously pushes food materials through a nozzle (as in a screw feeder). This system is particularly useful for extruding high viscosity materials (up to 104 Pas).

Mantihal, Prakash, Godoi and Bhandari (2017) developed a screw extrusion method for 3D printing chocolate. The advantage of the screw system is the ability to continuously dispense raw material, as the material can be drawn from a larger container and it is not necessary to stand a cartridge. Nevertheless, the screw system has so far been rarely used for printing food materials, which is perhaps due to the difficulty of cleaning the system.

In the case of some food materials such as chocolate or protein gel, the extruded layer must be at an elevated temperature, and a phase transition from liquid to solid structure at ambient temperature must occur after cooling. Therefore, the choice of printing temperature depends on the specific thermal properties of the materials, such as the melting point of chocolate and the gelation temperature of the protein dispersion.

As mentioned earlier, 3D printing technologies create products based on digital design files. In the case of extrusion-based 3D printing, the digital design file defines the planning of the printing path, which can be generated in three steps:

(i) Cartesian, delta, polar or scalar 3D printer configuration (Derossi, Caporizzi, Ricci, and Severini, 2019);
(ii) developing a digital model of the 3D structure using computer-aided design (CAD) programming;
(iii) generation of a control geometric code (G-code) that contains information for printer movement using slicing software. Using G-code commands, several important printing parameters can be controlled, such as extrusion speed (i.e. the speed at which the syringe or piston moves), nozzle speed (i.e. the speed at which the nozzle moves over the printing platform) and layer height (i.e. the distance between the nozzle and the previous printed layer).

These parameters significantly affect the printing result of a given recipe. Other parameters, such as printing temperature and nozzle configuration, also affect the printability of materials and the quality of final products. These two parameters are more related to the design of the printing system and their influence will be discussed after the presentation of technical solutions operating on the market.

2.2. Binder jetting, selective sintering and inkjet printing

In addition to extrusion, three other techniques, i.e. binder jetting, selective sintering printing (SLS) and inkjet printing, are useful for the manufacture of food products. Both binder jetting and selective sintering are powder-bed printing technologies.

Powder-bed printing technology uses operations to deposit powdered food materials as a thin layer on a printing platform, the layer is then aligned by a roller or blade. Then, following a digital design, the powder particles are combined according to the 2D layer cross-section of the designed shape, which is achieved by applying a liquid binder (in the case of binder jetting) or by sintering with an infrared laser beam or hot air (in the case of selective sintering). A new layer of powder is deposited after the previous layer has set, the construction platform is lowered by a certain layer thickness, after which a new layer of powder is deposited, aligned, and the process is repeated until the desired 3D shape is formed in the bed.

The advantage of powder-bed printing is the use of excess powder material as a support for the shape being produced. Unsintered powder provides the necessary support in designs that contain voids and overhangs, for which additional support structures must be printed in extrusion printing. After printing, the unused powder is removed and can be reused for the next printing. This advantage makes SLS more suitable for processing complex macroscopic designs. On a smaller length scale, SLS allows for greater spatial resolution, resulting in greater flexibility for the local adjustment of mechanical properties.

In laser sintering in particular, microscale properties are altered by changing the process parameters. In SLS, the most important process parameters are laser power, laser speed, hatch distance, or distance between scan lines, and layer thickness. SLS parameters can be easily changed locally, giving greater flexibility in changing local mechanical properties.

Noort, Van Bommel, and Renzetti (2017) investigated a wheat flour-based powder formulation with maltodextrin and palm-oil powder as binding ingredients that meet the thermal requirements for infrared laser beam sintering. By varying the thickness of the internal structures of the product during sintering (i.e. 1 mm of cell walls in the horizontal direction vs. 3 mm in the vertical direction), it was possible to produce a porous three-dimensional structure containing open cells, resulting in significant differences in the mechanical properties of the product depending on the breaking direction.

Inkjet printing is another 3D printing technique. It is the most commonly used technique for realising graphic decoration, filling surfaces or embedding cavities in bakery products such as cookies and cakes. There are two types of inkjet printing methods, namely continuous jet printing and droplet printing (Liu, Zhang, Bhandari, and Wang, 2017). Ink is ejected continuously through a piezoelectric crystal vibrating at a constant frequency in a continuous jet printer. Grood and Grood (2013) developed an inkjet 3D food printing technology and commercialised it as FoodJet printing.

The technology uses a system of pneumatic membrane nozzles that deposit droplets on a moving object (Godoi and Sangeeta Prakash, 2016), which has been used to print a wide variety of formulas such as pizza sauce, melted chocolate, cheese and butter. For example, by using multiple "print-cool-print" cycles, a layer of chocolate of varying thickness can be printed on the surface of food (Zhu, Ribberink, De Wit, Schutyser, and Stieger, 2020). In general, fast printing and good print quality can be achieved with this technique, however it may not be suitable for creating very complex 3D structures.

3. 3D printers available on market

The intensive development of additive printing technology used for the manufacture of food products has finally made it possible to develop, launch and market technical solutions that enable the use of this technology by the end user.

Table 1. 3D printers adapted for food printing available on the market
Tabela 1. Drukarki 3D dostosowane do druku żywności dostępne na rynku

Printer	Prints	Printer dimensions (mm)	Print dimensions (mm)	Weight (kg)	Nozzle diameter (mm)	Price
Print2Taste Mycusini	Chocolate	240 × 230 × 275	90 × 90 × 45	4.0	1,0	~$590
byFlow Focus	Thick pastes	440 × 325 × 460	208 × 228 × 150	8.0	0.8, 1.2, 1.6	$4,000
Choc Edge Choc Creator V2 Plus	Chocolate	425 × 450 × 420	180 × 180 × 40	18.0	0.8	$2,880
Felix Food 3D Printer	Pastes, Chocolate, Purees, Meat	723 × 380 × 554	220 × 195 × 170	13.0	1.6, 2.5, 3.5	od $3,600
Natural Machines Foodini	Pasty	458 × 430 × 430	257 (diameter) × 110 (height)	20.0	0.8, 1.4, 4.0	$6,000
Print4Taste Procusini 5.0	Pastes, Chocolate, Cassis, Marzipan, Fondant	600 × 600 × 650	250 × 150 × 100	9.0	0.5 / 1.3	$3,600
Wiiboox Sweetin	Pastes	192 × 380 × 420	100 × 100 × 75	10.0	0.4 to 1.55	$1,999
La Pâtisserie Numérique Patiss3	Pastes, powders	560 × 570 × 640	120 × 140 × 75	10.0	0.8, 1.2, 1.6	from $510 rent per month

Source: own work based on (the Internet)./Źródło: opracowanie własne na podstawie (Internet).

An analysis of the market has shown that the technical solutions that are at the stage of technical development enabling the development of a marketable product concern, without exception, the technology of extrusion, with the use of preloaded cartridges/syringes.

Today’s food printers work much like an FDM 3D printer, extruding edible pastes into precise shapes determined by both the 3D model and the G-code generation software. Although there are many limitations to the capabilities of these machines (especially in terms of the materials available for use), food printers have earned a place in the kitchens of top restaurants for their ability to deliver extravagantly designed dishes. Yet, the relatively high prices and the advanced operating skills required mean that 3D printers are still dedicated more to the organised food service – chefs and catering companies use these machines to differentiate their food from the others.

Neither standard software nor a 3D printer optimised for the specific challenges of printing food exist so far. The future prospects for the development of this technology should include the gathering of standardised digital recipes that consumers could download and use in their 3D printers, just as 3D printing enthusiasts can download designs for plastic toys or tools as 3D printing files. At the moment, a 3D-printing chef who wants to create any sophisticated recipe would have to painstakingly develop it from scratch – because not only does it have to be tasty, it has to be feasible.

The other topic in food 3D printing is related to food-safety. In general, there are three factors to consider for food-safe 3D elements: the design of the part, the materials used and post-processing. Food-safe means that a product meets the requirements for its intended use and will not cause a food safety risk. EU food regulations apply to all stages of production, processing and distribution of food and feed. European Regulation EC 1935/2004 provides guidelines for materials and objects intended for food contact to prevent contamination.

3.1. Print2Taste Mycusini

The Mycusini 2.0 food 3D printer is a solution of the German startup Print2Taste.

The Mycusini 2.0 is compact enough to fit on a kitchen counter or be stored in a cabinet. It uses a stainless steel cartridge, which is supplemented with chocolate supplied by the manufacturer. The new model comes in 5 colours with rounded corners and a removable platform for easy cleaning. The template library has also been updated, which includes over 1000 objects, as well as free access to the Mycusini Club, with which the own projects can be easily created.

Fig. 1. Mycusini 2.0 3D chocolate printer
Rys. 1. Drukarka 3D czekolady Mycusini 2.0

Source/Źródło: https://mycusini.com/.

3.2. byFlow Focus

Focus by ByFlow is a portable food printer that uses user-filled syringes to extrude designs onto a static plate. Used in professional kitchens and restaurants geared toward 3D printing, the Focus is a machine that allows chefs, pastry chefs, chocolatiers, and others to customise their products by printing edible objects in molds that are not possible to make by hand or with mould.

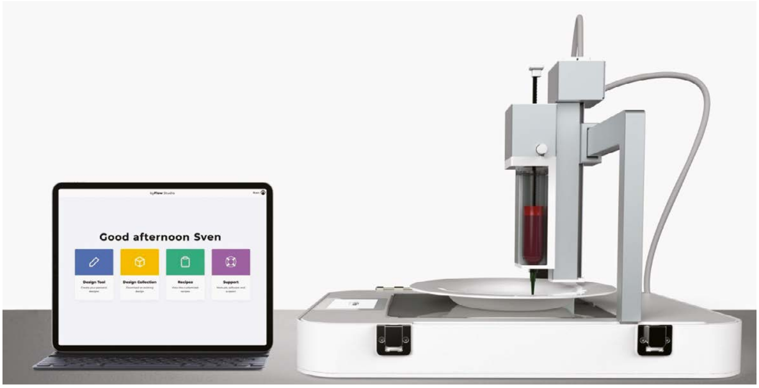

Fig. 2. Focus Food Printer
Rys. 2. Drukarka Focus Food

Source/Źródło: www.3dbyflow.com.

With the purchase of Focus, a 3-year licence for byFlow Studio is provided, a software to create and share the food projects with other users. Along with several food recipes for 3D printing, byFlow Studio presents a collection of over 100 different shapes. Several accessories are available from byFlow, such as additional print heads, nozzles and additional cartridges.

3.3. Choc Edge Choc Creator V2 Plus

Choc Creator V2 Plus, with the size of a desk and designed to be as user-friendly as possible, takes the tempered chocolate provided by the user, keeps it warm and extrudes it through a stainless steel nozzle designed to come into contact with food.

Fig. 3. Choc Creator V2 Plus
Rys. 3. Choc Creator V2 Plus

Source/Źródło: www.chocedge.com.

Choc Edge offers a wide range of software and applications to further enhance the capabilities of the printer. For design, the Choc Draw mobile app allows to freely scribble 2D designs that can be sent directly to the printer. Mix & Match, on the other hand, is a web application where users can generate simple text models and even customise other patterns available on the platform. Finally, Choc Print, their own slicer software, allows to print other models outside of their digital ecosystem.

The maximum Z-axis travel distance (40 mm) makes this machine best suited for 2D printing and decorative prints rather than oversized pieces of structural complexity.

3.4. Felix Food 3D Printer

After more than a decade of creating 3D printers, Felix Printer has finally entered the food printing market. It is one of the companies that also produces 3D printers for plastics as well as biomaterials. In 2022, under their spin-off Felix Food, three versions of the food 3D printer were released. All the models print numerous types of pastes, from vegetable purees to cakes and chocolates, each with precision and speed. Felix Food printers enable food creations, both at home, in a restaurant and as a research tool.

Fig. 4. Felix Food printers
Rys. 4. Drukarki Felix Food

Source/Źródło: https://www.felixprinters.com/.

Felix Single, with one nozzle, prints one material; Felix Twin has two nozzles for printing the same material at double speed; and Felix Switch, also with two nozzles, prints two different materials at the same time. These printers are designed for professionals and caterers looking to elevate their level of food creation.

3.5. Natural Machines Foodini

Natural Machines' Foodini printer can even print thick burgers with cranberries, walnuts and such like thanks to its wide range of nozzle sizes and wide cartridges. Designed to promote healthy eating and the ingenious (and convenient) formation of all natural foods, Foodini is used both in rehabilitation centres and in professional kitchens. Instead of a rectangular plate, Foodini has a round plate made of Pyrex glass – the same oven-resistant glass that is usually found in microwave ovens. The printing chamber is temperature-adjustable and the printer can hold up to five food-grade stainless steel capsules that are automatically replaced; all parts are washable.

Fig. 5. Foodini 3D food printer and accessories
Rys. 5. Drukarka 3D do żywności i akcesoria

Source/Źródło: https://www.naturalmachines.com.

3.6. Print4Taste Procusini 5.0

Arguably the most polished and plug-and-play food printer in this list, Procusini has a cartridge system for its raw materials. This means that the contact between the food and the device is limited to the nozzle, which is removable and dishwasher safe. Specially developed food cartridges are available for the Procusini device, including marzipan and four different types of chocolate (dark, white, pink and blue). During printing, these cartridges can be heated up to 60°C.

The newer version 5.0 has an LCD display for faster and simpler operation, often required in professional kitchens. A double extruder is also available, which allows to print two edible materials at the same time. The user also receives total access to their online platform – the Procusini Club, which reportedly contains thousands of ready-to-print templates, objects, texts and blank models. There are also video tutorials and tips on how to get the most out of this printer on how to make the most of the platform.

Fig. 6. Procusini 5.0
Rys. 6. Procusini 5.0

Source/Źródło: https://procusini.com/.

3.7. Wiiboox Sweetin

Positioned as a chocolate 3D printer, the Wiiboox Sweetin is actually a more generic food printer, enabling to extrude various foods from its thick extruder into the paste. The touchscreen interface should make it easier to use for anyone familiar with using a computer. It has an automatic leveling mechanism, freeing the user from tedious activities related to leveling the bed. Wiiboox provides a huge number of ready-to-print chocolate models for downloading. There is also their website design software that focuses on text, images, and simple model design.

Fig. 7. Sweetin 3D Food Printer
Rys. 7. Drukarka 3D do żywności Sweetin

Source/Źródło: https://www.wiiboox.com/3d-printer-wiiboox-sweetin.php.

3.8. La Pâtisserie Numérique Patiss3

The new (September 2022) printer from Parisian company The Digital Patisserie (La Pâtisserie Numérique) uses a powder-based process that makes it possible to work with classic puff pastry recipes, without any additives.

Fig. 8. Patiss3
Rys. 8. Patiss3

Source/Źródło: https://www.lapatisserienumerique.com.

Patiss3 can work with a wide range of edible raw materials. Currently, there are only 25 machines in production. Aimed at professionals, the printer can be rented for 500 euros per month only in Europe.

4. The advantages and drawbacks of existing solutions

Depending on the 3D printing technique used, there are varying problems that affect each of the possible techniques. In the case of extrusion-based printing, the advantages include the wide selection of food materials and the relative simplicity of the printing system. However, for example, printing on grain-based raw materials at high resolution remains a challenge, and it is often the case that the printed structure can deviate from the digital design, sometimes due to imperfections during printing, such as lack of continuous structure and loss of layer differentiation (e.g. structure collapse) (Pulatsu et al., 2020).

This is particularly problematic when the goal is to achieve a complex geometric pattern with detailed filling or a certain percentage of pores or voids. Therefore, when optimising the production process of 3D printed food, it is important to consider the impact of the formulation, printing settings and conditions used during post-printing processing on the properties and quality of the final products.

Printing temperature is a critical parameter for extrusion-based printing systems. Some raw materials, such as viscous vegetable paste, can be printed at room temperature and form a self-supporting 3D structure after deposition, while others, such as protein gels, require printing at elevated temperatures (Mantihal et al., 2017). For materials based on a starchy raw material (dough), increasing the temperature reduces its viscosity, hence less force is needed for the extrusion process, which can be beneficial when the extrusion force of the printing system is limited.

In extrusion-based printing it is possible to use various nozzle configurations, such as a single nozzle, a side-entry nozzle, a coaxial nozzle, and a compound nozzle designed for extrusion of multiple raw materials. Among these designs, the single nozzle can be used to print a single formulation (which is usually a mixture of multiple components) at the same time. It is the most commonly used design for extrusion printing of food materials due to its simplicity, but it does not usually allow for controlling the spatial distribution of different formulations within the food matrix. In a single-nozzle system, on the other hand, the spatial distribution of ingredients can be realised by changing the nozzle configuration.

Schutyser et al. (2018) designed and tested a side-entry dispenser to introduce a second liquid phase into the deposited main formulation and, based on precise control of dispensing pressure, deposited two phases simultaneously. On the other hand, the so-called concentric nozzle configuration can be used to realize a different type of ingredient distribution. In coaxial printing, a single filament can be formed that has a core of one formulation and an outer layer or coating of another formulation. Uribe-Wandurraga et al. (2020) used coaxial extrusion to hide a dark green cake enriched with microalgae inside a regular cake to produce snacks with a more acceptable colour. In addition, a spatial arrangement of food materials and complex food products with multiple textures and multiple flavours can be obtained using a printer with multiple print heads (e.g. dual nozzle 3D printing (Liu, Zhang, and Yang, 2018)).

In extrusion-based systems it is necessary to consider the design in terms of food safety. Cartridge/syringe systems are properly suited because a plastic syringe cap is often placed between the plunger/air and the food material. However, their operating characteristics are intermittent, unlike the screw system. Material moved by a screw allows the use of a larger raw material tank from which the screw draws material continuously (like a screw feeder), but in this case the risk of contamination must be taken into account, since the screw is in direct contact with food materials.

To sum up, by using different nozzle designs or printing systems it is possible to produce 3D printed food with complex geometric patterns as well as spatial distribution of ingredients. By changing the recipes and print settings used, the macro and/or microstructure of the printed food can be shaped.

However, the 3D printing of many food materials may require a new printing system design, as multi-material voxelated structures cannot be easily generated by extruding monolithic cylindrical filaments layer by layer.

3D printed products often require post-process heat treatment to produce edible products. Some common post-processing technologies for 3D printed bakery foods include baking, drying, frying, steaming and microwave treatment. Post-processing affects the quality of final products in terms of colour, shape and textural properties. In particular, the thermal binding of protein and starch components and the evaporation of moisture regulates the transition of viscoelastic dough material to the desired texture of baked goods, such as a soft, spongy dough or a crispy cookie. In addition, baked goods' flavour and brown colour are the result of chemical reactions, such as the Maillard reaction or caramelisation of sugars. Conventional bakery products almost always change their shape during baking, such as the expansion of the dough or the spreading of the cookie.

In the case of 3D printed bakery products, such deformation during post-baking processing is highly undesirable, as it causes the loss of the original 3D printed shape. Heating, however, can often reduce viscosity and thus induce material flow, meaning that the product loses its 3D shape during post-processing (Liu et al., 2017). Additionally, an expansion of the 3D structure can occur during baking due to the presence of grout in the printing material. Such expansion can result in significant deformation of the carefully embedded design, which can lead to unsuccessful printing results after baking.

Similarly, the originally formed shape of the 3D printed structure may collapse (Lille, Kortekangas, Heinio, and Sozer, 2020) or shrink (Pulatsu et al., 2020) or otherwise change during baking. In some cases, the volume of 3D printed bakery products can also increase during post-processing. For example, a 3D-printed rice cake could swell during steaming due to the high amylopectin content of the waxy rice that was used. This expansion caused instability in the 3D structure (Liu et al., 2020).

One exception is 3D printed cereal products created by selective laser sintering (SLS, see Section 2.2). Since the food powders are heat-treated with an infrared laser beam, in principle no further post-processing is needed (Noort et al., 2017). In addition, the type of post-processing treatment used can affect the mechanical properties of the final products. For example, Noort et al. (2017) reported higher hardness of grain-based structures produced by SLS after post-processing with hot steam compared to baked and untreated samples. They attributed the strengthening of the printed structure to the introduction of moisture into the matrix via wet steam, which enables reactions such as starch gelatinisation and protein denaturation.

Selective laser sintering is a 3D printing technique that allows for product shape design and the local control of mechanical properties. SLS, therefore, offers unique possibilities for personalising the texture of food products. Compared to extrusion--based printing, powder-bed printing has some advantages; in particular, powder-bed printing can be performed at relatively high speeds and also exhibits greater design freedom in terms of geometry, as the uncured powder can provide support for the shape being created. Powder-bed printing can be used to print spatial designs with variations in textures and flavours.

One of the challenges for powder-bed printing, however, is the limited choice of food materials with good bonding/binding properties. So far, the food materials that have been explored for powder bed printing are rather limited. Sugar and fat-based powder formulations have been reported, but they may be considered less nutritious (Liu et al., 2017). Another challenge for powder-bed printing is printing resolution, especially when significant moisture content is required in the final products. With binder jetting, the liquid binder can flow into adjacent voxels, reducing printing precision. Molten powder can also shrink or expand during printing, causing unwanted changes in the printed structure or even printing failure.

Therefore, the development of new powder formulations (or powder-binder combinations) and the optimisation of the powder-bed printing process are interesting research topics to expand the range of ingredients and improve the quality of the final products.

5. Conclusions

The strong individualisation of food consumption due to health and dietary preferences is increasing the demand for super personalised foods (Aguilera and Park, 2016; Lipton, 2017; Aguilera, 2018; Escalante-Aburto, Trujillo-de Santiago, Alvarez, and Chuck-Hernandez, 2021). 3D printing techniques have the potential to meet the need for food personalisation while maintaining a favourable economic aspect.

It is worth mentioning that 3D printers are not able to produce food – only a change in the form of the material takes place in them. The given material must meet certain conditions: the main one being the ability to give it the consistency of a paste or puree, through grinding or melting. A common feedstock for food 3D printers are vegetables, such as broccoli or spinach. Another frequently used material in food 3D printing technology is chocolate. Its key advantage in this context is that it is easy to liquefy and take any shape. Today, chocolate printers are used primarily to create decorations for cakes and desserts.

The 3D printing of food not only makes it possible to give it a specific shape, but also provides full control over the nutritional content and composition of the printed meals. These are key features when feeding people who require special diets, e.g. athletes, children and the elderly or hospital patients, among others, for whom a properly composed diet is a key issue.

3D food, or food from a 3D printer, also makes it possible to change the consistency of products while maintaining the original shape. The original material can be shredded and shaped anew, which solves the problem of taking hard and hard-

-to-eat foods by people with dental problems, who, thanks to innovative solutions, can again enjoy their favourite dishes without restrictions.

The mechanism of 3D food reshaping can be used in the nutrition of children, as well as the elderly and people with dysphagia – unpopular pureed fruits and vegetables thanks to 3D printing can take on an attractive shape, which will encourage everyone to eat them. Free-form 3D printed food products also work well for vegans and vegetarians, as well as people trying to change their eating habits. Attractive-looking, balanced meals printed from vegetables can be an excellent alternative to meat and zoonotic products.

3D printing also makes it possible to control some of the parameters of the resulting products. Biologically, the density and physical structure of the food is important. With proper design of the target 3D printing, the product can be bulked up or given a structure that is better absorbed by the human digestive system. Food in the human body is digested superficially, so greater dilution of molecules in 3D printer food products will result in faster breakdown into absorbable parts in the intestines. This process can also be carried out the other way around, thickening the structure leads to a reduction in absorption, thus controlling absorption.

3D printing may also be a way to address the huge food waste we face in the 21st century. A large percentage of food discarded due to its unappetising appearance can be reused. A 3D printer can easily give them a new, aesthetically pleasing shape. Currently, several places around the world are striving to patent solutions that will allow making food from food scraps simple and cost-effective. In times of climate crisis and growing environmental awareness, this is of great importance.

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